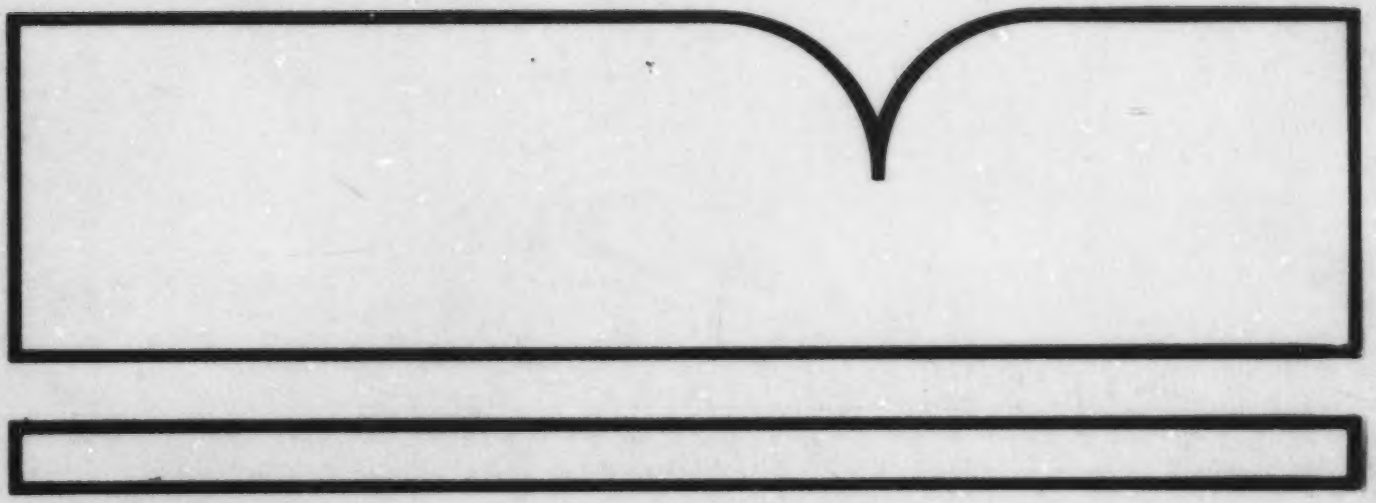
PB86-224961

Criteria for Identifying Areas of Vulnerable Hydrogeology under the Resource Conservation and Recovery Act. Appendix A. Technical Methods for Evaluating Hydrogeologic Parameters

(U.S.) Environmental Protection Agency
Washington, DC

Jul 86



U.S. Department of Commerce
National Technical Information Service
NTIS

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. 530-SW-86-022A	2.	3. Recipient's Accession No. PB86 224961/AS
4. Title and Subtitle: Appendix A- Technical Methods for Evaluating Hydrogeologic Parameters			5. Report Date: ~~August~~ July 1986
7. Author(s): Office of Solid Waste			8. Performing Organization Rept. No.
9. Performing Organization Name and Address: Land Disposal Branch (WH-565E), Waste Management Division, U.S. Environmental Protection Agency, 401 M St. SW, Washington D.C. 20460			10. Project/Task/Work Unit No.
			11. Contract(C) or Grant(G) No. (C) 68-01-6871 (G)
12. Sponsoring Organization Name and Address: Same as above			13. Type of Report & Period Covered: Guidance Manual, ongoing
			14.

15. Supplementary Notes

Appendix to Support the Main Text: Criteria for Identifying Areas of Vulnerable Hydrogeology Under the Resource Conservation and Recovery Act- RCRA Statutory Interpretive Guidance

16. Abstract (Limit: 200 words)

Appendix A describes how to determine hydraulic conductivity, hydraulic gradient, and effective porosity. An abbreviated version of EPA's Method 9100 is included to supplement the hydraulic conductivity discussion. Appendix A contains a detailed discussion on how to consider seasonal fluctuations in hydraulic gradients when calculating ground-water time-of-travel.

17. Document Analysis a. Descriptors

Hazardous Waste; Land Treatment, Storage, and Disposal Facilities; Location, Hydrogeology

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release Unlimited	Unclassified	
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

United States
Environmental Protection
Agency

Office of Solid Waste
and Emergency Response
Washington DC 20460

July 1986

Solid Waste

PB86-224961

EPA

Criteria for Identifying Areas of Vulnerable Hydrogeology Under the Resource Conservation and Recovery Act

Appendix A

Technical Methods for Evaluating Hydrogeologic Parameters

Interim Final

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FIELD METHODS TO DETERMINE HYDRAULIC CONDUCTIVITY

SECTION 1.0

This section discusses methods available for the determination of fluid conductivity under field conditions. As most of these tests will use water as the testing fluid, either natural formation water or water added to a borehole or piezometer, the term hydraulic conductivity will be used for the remainder of this section. Before testing for hydraulic conductivity, the first step is to characterize the geology of the site. This initial characterization will aid in the design of well locations. The investigator should consult the RCRA Ground-Water Monitoring Technical Enforcement Guidance Document, U.S.EPA (Draft) 1985 (TEGD) for information on site characterization.

The owner/operator must identify areas of high and low hydraulic conductivity (K) within each formation, because such variations in K can create irregularities in ground water flow paths. Areas of high hydraulic conductivity represent areas of greater ground water flow and, if contaminants are present, zones of potential migration.

Hydraulic conductivity measurements must define both vertical and horizontal hydraulic conductivity across an owner/operator's regulated site. In assessing the completeness of an owner/operator's hydraulic conductivity measurements, the reviewer

should also consider results from the boring program used to characterize the site geology. Zones of high permeability or fractures identified from drilling logs should have been considered in the determination of hydraulic conductivity. Additionally, information from coring logs can be used to refine the data generated by slug or pump tests.

The location of wells, selection of screened intervals, and the appropriate tests depend upon the specific site under investigation. The person responsible for such selections should be a qualified hydrogeologist or geotechnical engineer experienced in the application of established principles of contaminant hydrogeology and ground water hydraulics.

To estimate hydraulic conductivity, single well methods are the preferred method since they do not average the effects of geologic heterogeneities. In addition, the methods for field determination of hydraulic conductivity are restricted to well or piezometer tests applicable below existing water tables. Determination of travel times of leachate and dissolved solutes above the water table usually require the application of unsaturated flow theory. Methods for calculating travel times in unsaturated zones are detailed in Appendix C.

Standard reference texts on ground water hydraulics and contaminant hydrogeology that should be consulted include: Bear (1972), Bouwer (1978), Freeze and Cherry (1979), Stallman (1971), and Walton (1970).

1.1 WELL-CONSTRUCTION CONSIDERATIONS

The purpose of using properly constructed wells for hydraulic conductivity testing is to assure that test results reflect conditions in the geologic interval being tested, rather than the conditions caused by well construction. In all cases, diagrams showing all details of the actual well or borehole constructed for the test should be made, as well as detailed narrative description.

Detailed discussions of well installation, construction, and development methods are given by Bouwer (1978), pages 160-180, Acker (1974), Johnson (1975), and the TEGD, Chapter 3.

The TEGD should be consulted for information concerning well drilling, construction, and development considerations. However, the TEGD is concerned primarily with ground water quality monitoring wells. Boreholes suitable for measuring hydraulic conductivity may not necessarily also be suitable for ground water quality monitoring, due to considerations unique to monitoring (such as the need for inert casing, possible need for pumps to be installed, etc.). The TEGD discusses these differences in more detail.

1.1.1 Wells Requiring Well Screens

Well screens placed opposite the interval to be tested should be constructed of materials that are compatible with the fluids to be encountered. The screen slot size should be determined to minimize the inflow of fine-grained material to the well during development and testing. In addition, hydraulic conductivity

information generally provides average values for the entire area across a well screen. For more depth discrete information, well screens will have to be shorter. If the average hydraulic conductivity for a formation is required, entire formations may have to be screened. Bouwer (1978), and Johnson (1975) give a summary of guidelines for sizing well screens.

The annulus between the well screen and the borehole should be filled with an artificial gravel pack or sand filter. Guidelines for sizing these materials are given by Johnson (1975). For very coarse materials, it may be acceptable to allow the materials from the tested zone to collapse around the screen forming a natural gravel pack.

The screened interval should be isoloated from overlying and underlying zones by materials of low hydraulic conductivity. Generally, a short bentonite plug is placed on top of the material surrounding the screen, and cement grout is placed in the borehole to the next higher screened interval (in the case of multiple screen wells), or to the land surface for single screen wells.

Although considerations for ground water quality sampling may dictate different minimum casing and screen diameters, the recommended guideline for hydraulic conductivity characterization studies is that wells to be tested by pumping, bailing, or injection in coarse-grained materials should be at least 4 inches inside diameter. Wells to be used for testing materials of low hydraulic

conductivity by sudden removal or injection of a known volume of fluid should be constructed with as small a casing diameter as possible to maximize measurement resolution of fluid level changes. Casing sizes of 1.25 to 1.50 inches usually allow this resolution while enabling the efficient sudden withdrawal of water for these tests.

1.1.2 Wells Not Requiring Well Screens

If the zone to be tested is sufficiently indurated that a well screen and casing is not required to prevent caving, then it is preferable to use a borehole open to the zone to be tested. These materials generally are those having low to extremely low hydraulic conductivities. Consolidated rocks having high conductivity because of the presence of fractures and solution openings may also be completed without the use of a screen and gravel pack. Uncased wells may penetrate several zones for which hydraulic conductivity test are to be run. In these cases, the zones of interest may be isolated by the use of inflatable packers.

1.2 WELL DEVELOPMENT

For wells that are constructed with well screens and gravel packs, and for all wells in which drilling fluids have been used that may have penetrated the materials to be tested, adequate development of the well is required to remove these fluids and to remove the fine-grained materials from the zone around the well screen. Development is carried out by methods such as intermittent pumping, jetting with water, surging, and

bailing. Adequate development is required to assure maximum communication between fluids in the borehole and the zone to be tested. Results from test run in wells that are inadequately developed will include an error caused by loss of fluid potential across the undeveloped zone, and computed hydraulic conductivities will be lower than the actual value. Bouwer (1978), Johnson (1975), and the TEGD give further details on well development including methods to determine when adequate development has occurred.

1.3 DATA INTERPRETATION AND TEST SELECTION CONSIDERATIONS

Hydraulic conductivity may be determined in wells that are either cased or uncased as described in Section 1.1. The tests all involve disturbing the existing fluid potential in the tested zone by withdrawal from or injection of fluid into a well either as a slug over an extremely short period of time, or by continuous withdrawal or injection of fluid. The hydraulic conductivity is determined by measuring the response of the water level or pressure in the well as a function of time since the start of the test. Many excellent references are available that give the derivation and use of the methods that are outlined below, including Bouwer (1978), Walton (1969), and Lohman (1972).

The selection of a particular test method and data analysis technique requires the consideration of the purposes of the test, and the geologic framework in which the test is to be run. Knowledge of the stratigraphic relationships of the zone to be tested and both overlying and underlying materials should always be used to select appropriate test design and data interpretation methods.

The equations given for all computational methods given here and in the above references are based on idealized models comprising layers of materials of different hydraulic conductivities. The water-level response caused by disturbing the system by the addition or removal of water can be similar for quite different systems. For example, the response of a water-table aquifer and a leaky, confined aquifer to pumping can be very similar. Consequently, it is not considered acceptable practice to obtain data from a hydraulic conductivity test and interpret the type of hydraulic system present without supporting geologic evidence.

The well test methods are discussed under the following two categories: 1) methods applicable to coarse-grained materials and tight to extremely tight materials under confined conditions; and 2) methods applicable to unconfined materials of moderate

permeability. The single well tests integrate the effects of heterogeneity and anisotropy. The effects of boundaries such as streams or less permeable materials usually are not detectable with these methods because of the small portion of the geologic unit that is tested.

1.4 SINGLE WELL TESTS

The tests for determining hydraulic conductivity with a single well are discussed below based on methods for confined and unconfined conditions. The methods are usually called slug tests because the test involves removing a slug of water instantaneously from a well and measuring the recovery of water in the well. The method was first developed by Hvorslev (1951), whose analysis did not consider the effect of fluid stored in the well. Cooper and others (1967) developed a method that considers well bore storage. However, their method only applies to wells that are open to the entire zone to be tested and that tap confined aquifers. Because of the rapid water-level response in coarse materials, the tests are generally limited to zones with a transmissivity of less than about 70 cm^2/sec (Lohman, 1972). The method has been extended to allow testing of extremely tight formations by Bredehoeft and Papadopulos (1980). Bouwer and Rice (1976) developed a method for analyzing slug tests for unconfined aquifers.

1.4.1 Method for Moderately Permeable Formations Under Confined Conditions

1.4.1.1 Applicability. This method is applicable for testing zones to which the entire zone is open to the well screen or

open borehole. The method usually is used in materials of moderate hydraulic conductivity which allow measurement of water-level response over a period of an hour to a few days. More permeable zones can be tested with rapid response water-level recording equipment. The method assumes that the tested zone is uniform in all radial directions from the test well. Figure 1.4-1 illustrates the test geometry for this method.

1.4.1.2 Procedures. The slug test is run by utilizing some method of removing a known volume of water from the well bore in a very short time period and measuring the recovery of the water level in the well. The procedures are the same for both unconfined and confined aquifers. Water is most effectively removed by using a bailer that has been allowed to fill and stand in the well for a sufficiently long period of time so that any water-level disturbance caused by the insertion of the bailer will have reached equilibrium. In permeable materials, this recovery time may be as little as a few minutes. An alternate method of effecting a sudden change in water level is the withdrawal of a weighted float. The volume of water displaced can be computed using the known submersed volume of the float and Archimedes' principle (Lohman, 1972).

Water-level changes are recorded using either a pressure transducer and a strip chart recorder, a weighted steel tape, or an electric water-level probe. For testing permeable materials that approach or exceed 70 cm^2/sec, a rapid-response transducer/recorder system is usually used because essentially full recovery may occur in a few minutes. Because the rate of water-level response decays with time, water-level or pressure

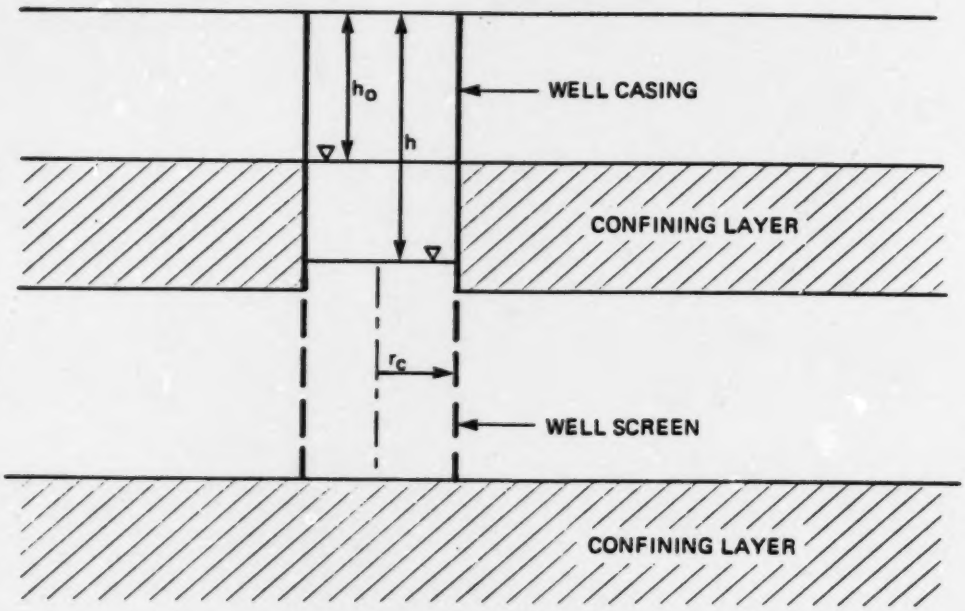

Figure 1.4-1--Geometry and variable definition for slug tests in confined aquifers.

changes should be taken at increments that are approximately equally spaced in the logarithm of the time since fluid withdrawal. The test should be continued until the water level in the well has recovered to at least 85 percent of the initial pre-test value.

1.4.1.3 Calculations. Calculations for determining hydraulic conductivity for moderately permeable formations under confined conditions can be made using the following:

a. Determine the transmissivity of the tested zone by plotting the ratio h/h_o on an arithmetic scale against time since removal of water (t) on a logarithmic scale. The observed fluid potential in the well during the test as measured by water level or pressure is h, and h_o is the fluid potential before the instant of fluid withdrawal. The data plot is superimposed on type curves, such as those given by Lohman (1972), Plate 2 or plotted from Table 1.4-1 with the h/h_o and time axes coincident. The data plot is moved horizontally until the data fits one of the type curves. A value of time on the data plot corresponding to a dimensionless time (β) on the type curve plot is chosen, and the transmissivity is computed from the following:

$$T = \frac{\beta r_c^2}{t}, \qquad (1)$$

where r_c is the radius of the casing (Lohman, 1972, p. 29).

TABLE 1.4-1

Values of the function $F(\alpha,\beta)$ for use in the conventional and pressurized slug tests. Source: Papadopulos et.al. (1973)

Tt/r_c^2	$\alpha = 10^{-6}$	$\alpha = 10^{-7}$	$\alpha = 10^{-8}$	$\alpha = 10^{-9}$	$\alpha = 10^{-10}$
0.001	0.9994	0.9996	0.9996	0.9997	0.9997
0.002	0.9989	0.9992	0.9993	0.9994	0.9995
0.004	0.9980	0.9985	0.9987	0.9989	0.9991
0.006	0.9972	0.9978	0.9982	0.9984	0.9986
0.008	0.9964	0.9971	0.9976	0.9980	0.9982
0.01	0.9956	0.9965	0.9971	0.9975	0.9978
0.02	0.9919	0.9934	0.9944	0.9952	0.9958
0.04	0.9848	0.9875	0.9894	0.9908	0.9919
0.06	0.9782	0.9819	0.9846	0.9866	0.9881
0.08	0.9718	0.9765	0.9799	0.9824	0.9844
0.1	0.9655	0.9712	0.9753	0.9784	0.9807
0.2	0.9361	0.9459	0.9532	0.9587	0.9631
0.4	0.8828	0.8995	0.9122	0.9220	0.9298
0.6	0.8345	0.8569	0.8741	0.8875	0.8984
0.8	0.7901	0.8173	0.8383	0.8550	0.8686
1.0	0.7489	0.7801	0.8045	0.8240	0.8401
2.0	0.5800	0.6235	0.6591	0.6889	0.7139
3.0	0.4554	0.5033	0.5442	0.5792	0.6096
4.0	0.3613	0.4093	0.4517	0.4891	0.5222
5.0	0.2893	0.3351	0.3768	0.4146	0.4487
6.0	0.2337	0.2759	0.3157	0.3525	0.3865
7.0	0.1903	0.2285	0.2655	0.3007	0.3337
8.0	0.1562	0.1903	0.2243	0.2573	0.2888
9.0	0.1292	0.1594	0.1902	0.2208	0.2505
10.0	0.1078	0.1343	0.1620	0.1900	0.2178
20.0	0.02720	0.03343	0.04129	0.05071	0.06149
30.0	0.01286	0.01448	0.01667	0.01956	0.02320
40.0	0.008337	0.008898	0.009637	0.01062	0.01190
50.0	0.006209	0.006470	0.006789	0.007192	0.007709
60.0	0.004961	0.005111	0.005283	0.005487	0.005735
80.0	0.003547	0.003617	0.003691	0.003773	0.003863
100.0	0.002763	0.002803	0.002845	0.002890	0.002938
200.0	0.001313	0.001322	0.001330	0.001339	0.001348

TABLE 1.4-1, continued

Extended values of $F(\alpha,\beta)$ for use in slug tests.
Source: Bredehoeft and Papadopulos (1980).

β	α=0.1	α=0.2	α=0.5	α=1	α=2	α=5	α=10
0.0000001	0.9993	0.9990	0.9984	0.9977	0.9968	0.9948	0.9923
0.0000002	0.9990	0.9986	0.9977	0.9968	0.9955	0.9927	0.9894
0.0000004	0.9986	0.9980	0.9968	0.9955	0.9938	0.9898	0.9853
0.0000006	0.9982	0.9975	0.9961	0.9945	0.9922	0.9876	0.9822
0.0000008	0.9980	0.9971	0.9955	0.9936	0.9910	0.9857	0.9796
0.000001	0.9977	0.9966	0.9945	0.9929	0.9900	0.9841	0.9773
0.000002	0.9968	0.9955	0.9925	0.9900	0.9858	0.9776	0.9683
0.000004	0.9955	0.9936	0.9890	0.9858	0.9801	0.9687	0.9558
0.000006	0.9944	0.9922	0.9877	0.9827	0.9757	0.9619	0.9464
0.000008	0.9936	0.9909	0.9858	0.9800	0.9720	0.9562	0.9387
0.00001	0.9929	0.9899	0.9841	0.9777	0.9688	0.9512	0.9318
0.00002	0.9898	0.9857	0.9774	0.9687	0.9562	0.9321	0.9059
0.00004	0.9855	0.9797	0.9685	0.9560	0.9385	0.9061	0.8711
0.00006	0.9822	0.9752	0.9615	0.9465	0.9258	0.8869	0.8458
0.00008	0.9794	0.9713	0.9557	0.9385	0.9151	0.8711	0.8253
0.0001	0.9769	0.9679	0.9505	0.9315	0.9057	0.8576	0.8079
0.002	0.9670	0.9546	0.9307	0.9048	0.8702	0.8075	0.7450
0.004	0.9528	0.9357	0.9031	0.8686	0.8232	0.7439	0.6684
0.006	0.9417	0.9211	0.8825	0.8419	0.7896	0.7001	0.6178
0.008	0.9322	0.9089	0.8654	0.8202	0.7626	0.6662	0.5797
0.01	0.9238	0.8982	0.8506	0.8017	0.7400	0.6384	0.5492
0.02	0.8904	0.8562	0.7947	0.7336	0.6595	0.5450	0.4517
0.04	0.8421	0.7980	0.7214	0.6489	0.5654	0.4454	0.3556
0.06	0.8048	0.7544	0.6697	0.5919	0.5055	0.3872	0.3030
0.08	0.7734	0.7190	0.6286	0.5486	0.4618	0.3469	0.2682
0.1	0.7459	0.6885	0.5951	0.5137	0.4276	0.3168	0.2428
0.2	0.6418	0.5774	0.4796	0.4010	0.3234	0.2313	0.1740
0.4	0.5095	0.4458	0.3566	0.2902	0.2292	0.1612	0.1207
0.6	0.4227	0.3642	0.2864	0.2311	0.1817	0.1280	0.09616
0.8	0.3598	0.3072	0.2397	0.1931	0.1521	0.1077	0.08134
1.	0.3117	0.2668	0.2081	0.1663	0.1315	0.09375	0.07120
2.	0.1786	0.1519	0.1202	0.09912	0.08044	0.05940	0.04620
4.	0.08761	0.07698	0.06420	0.05521	0.04668	0.03621	0.02908
6.	0.05527	0.04895	0.04331	0.03830	0.03328	0.02663	0.02185
8.	0.03943	0.03658	0.03254	0.02933	0.02594	0.02125	0.01771
10.	0.03065	0.02870	0.02600	0.02376	0.02130	0.01774	0.01499
20.	0.01498	0.01361	0.01268	0.01219	0.01133	0.009943	0.008716
40.	0.006690	0.006168	0.005774	0.006171	0.005897	0.005395	0.004898
60.	0.004367	0.004318	0.004229	0.004132	0.003994	0.003726	0.003445
80.	0.003242	0.003214	0.003163	0.003105	0.003022	0.002853	0.002668
100.	0.002577	0.002559	0.002526	0.002487	0.002431	0.002313	0.002181
200.	0.001271	0.001264	0.001258	0.001247	0.001230	0.001194	0.001149
400.	0.0006307	0.0006295	0.0006272	0.0006242	0.0006195	0.0006085	0.0005944
600.	0.0004197	0.0004188	0.0004177	0.0004163	0.0004141	0.0004087	0.0004016
800.	0.0003140	0.0003137	0.0003131	0.0003123	0.0003110	0.0003078	0.0003035
1000.	0.0002510	0.0002508	0.0002504	0.0002496	0.0002486	0.0002469	0.0002440

The type curves plotted using data in Table 1.4-1 are not to be confused with those commonly referred to as 'Theis Curves' which are used for pumping tests in confined aquifers (Lohman, 1972). The type curve method is a general technique of detemining aquifer parameters when the solution to the descriptive flow equation involves more than one unknown parameter. Although both the storage coefficient and transmissivity of the tested interval can be determined with the type curve method for slug tests, determination of storage coefficients is beyond the scope of this report. See Section 1.4.1.4 for further discussion of the storage coefficient.

If the data in Table 1.4-1 are used, a type curve for each value of α is prepared by plotting $F(\alpha,\beta)$ on the arithmetic scale and dimensionless time (β) on the logarithmic scale of semi-log paper.

b. Determine the hydraulic conductivity by dividing the transmissivity by the thickness of the tested zone.

1.4.1.4 Sources of Error. The errors that can arise in conducting slug tests can be of three types: those resulting from the well or borehole construction, measurement errors, and data analysis error.

Well construction and development errors. This method assumes that the entire thickness of the zone of interest is open to

the well screen or boreholes and that flow is principally radial. If this is not the case, the computed hydraulic conductivity may be too high. If the well is not properly developed, the computed conductivity will be too low.

Measurement errors can result from determining or recording the fluid level in the borehole and the time of measurement incorrectly. Water levels should be measured to at least an accuracy of 1 percent of the initial water-level change. For moderately permeable materials, time should be measured with an accuracy of fractions of minutes, and for more permeable materials, the time should be measured in terms of seconds or fractions of seconds. The latter may require the use of a rapid-response, pressure transducer and recorder system.

Data analysis errors. The type curve procedure requires matching the data to one of a family of type curves, described by the parameter α, which is a measure of the storage in the well bore and aquifer. Papadopulos and others (1973) show that an error of two orders of magnitude in the selection of α would result in an error of less than 30 percent in the value of transmissivity determined. Assuming no error in determining the thickness of the zone tested, this is equivalent to a 30 percent error in the hydraulic conductivity.

1.4.2 Methods For Extremely Tight Formations Under Confined Conditions

1.4.2.1 Applicability. This test is applicable to materials that have low to extremely low permeability such as silts,

clays, shales, and indurated lithologic units. The test has been used to determine hydraulic conductivities of shales of as low as 10^{-10} cm/sec.

1.4.2.2 Procedures. The test described by Bredehoeft and Papadopulos (1980) and modified by Neuzil (1982) is conducted by pressurizing suddenly a packed off zone in a portion of a borehole or well. The test is conducted using a system such as shown in Figure 1.4-2. The system is filled with water to a level assumed to be equal to the prevailing water level. This step is required if sufficiently large times have not elapsed since the drilling of the well to allow full recovery of water levels. A pressure transducer and recorder are used to monitor pressure changes in the system for a period prior to the test to obtain pressure trends preceding the test. The system is pressurized by addition of a known volume of water with a high-pressure pump. The valve is shut and the pressure decay is monitored. Neuzil's modification uses two packers with a pressure transducer below the bottom packer to measure the pressure change in the cavity and one between the two packers to monitor any pressure change caused by leakage around the bottom packer.

1.4.2.3 Calculations. The modified slug test as developed by Bredehoeft and Papadopulos (1980) considered compressive storage of water in the borehole. These authors considered that the volume of the packed-off borehole did not change

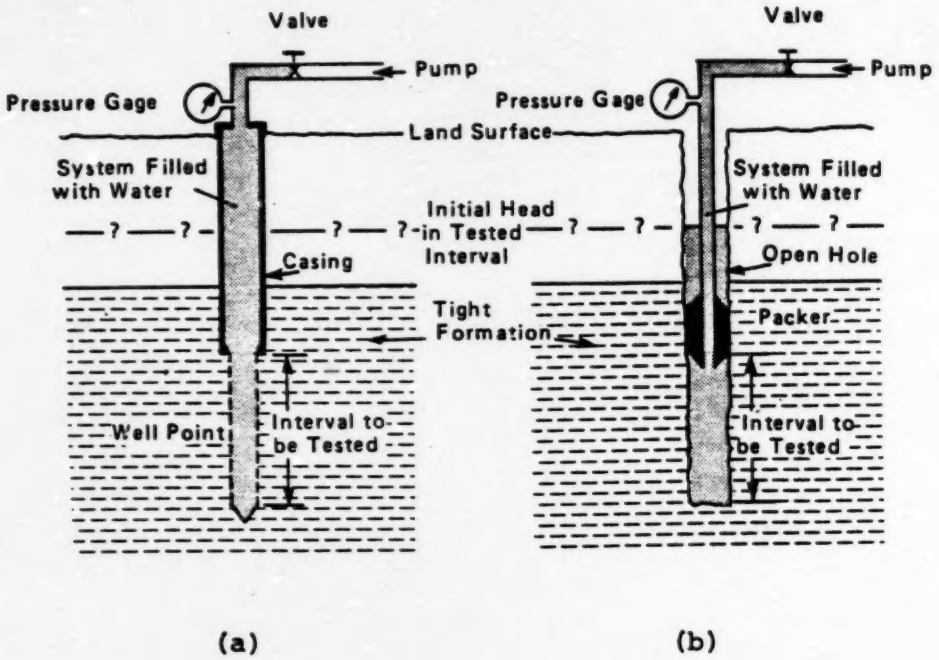

Figure 1.4-2 --Schematic diagram for pressurized slug test method in unconsolidated (a) and consolidated (b) materials. Source: Papadopulos and Bredehoeft, 1980.

during the test and that all compressive storage resulted in compression of water under the pressure pulse. Neuzil (1982) demonstrated that under some test conditions this is not a valid assumption. The computational procedure is the same in either case. Data is plotted in the same manner as for the conventional slug test and type curves are used from either Lohman (1972, Plate 2) or plotted from data given in Table 1.4-1 as described in Section 1.1.1.3. The value of time (t) and dimensionless time, (β), are determined in the same manner as for the conventional tests. If compression of water only is considered, transmissivity is computed by replacing r_c^2 by the quantity ($V_w\ C_w \rho\ g/\pi$) in Equation 2.

$$T = \frac{\beta(V_w\ C_w\ \rho g/\pi)^2}{t}\ , \qquad (2)$$

where

V_w is the volume of water in the packed-off cavity, L^3;
C_w is the compressibility of water, $LT^{2}M^{-1}$,
ρ is the density of water ML^{-3}; and
g is the accleration of gravity, LT^{-2}.

If the compressive storage is altered by changing the volume of the packed-off cavity (V), then the combined compressibility of the water and the expansion of the cavity (C_o) is used. C_o is computed by measuring the volume of water injected during

pressurization (ΔV) and the pressure change ΔP for the pressurization:

$$C_o = \frac{\Delta V}{V \Delta P} \qquad (3)$$

(Neuzil, 1982, page 440). Use of C_o requires an accurate method of metering the volume of water injected and the volume of the cavity.

1.4.2.4 Sources of Error. The types of errors in this method are the same as those for the conventional slug test. Errors may also arise by inaccurate determination of the cavity volume and volume of water injected. An additional assumption that is required for this method is that the hydraulic properties of the interval tested remain constant throughout the test. This assumption can best be satisfied by limiting the initial pressure change to a value only sufficiently large enough to be measured (Bredehoeft and Papadopulos, 1980).

1.4.3 Methods for Moderately Permeable Materials Under Unconfined Conditions

1.4.3.1 Applicability. This method is applicable to wells that fully or partially penetrate the interval of interest (Figure 1.4-3). The hydraulic conductivity determined will be principally the value in the horizontal direction (Bouwer and Rice, 1976).

1.4.3.2 Procedures. A general method for testing cased wells that partly or fully penetrate aquifers that have a water table

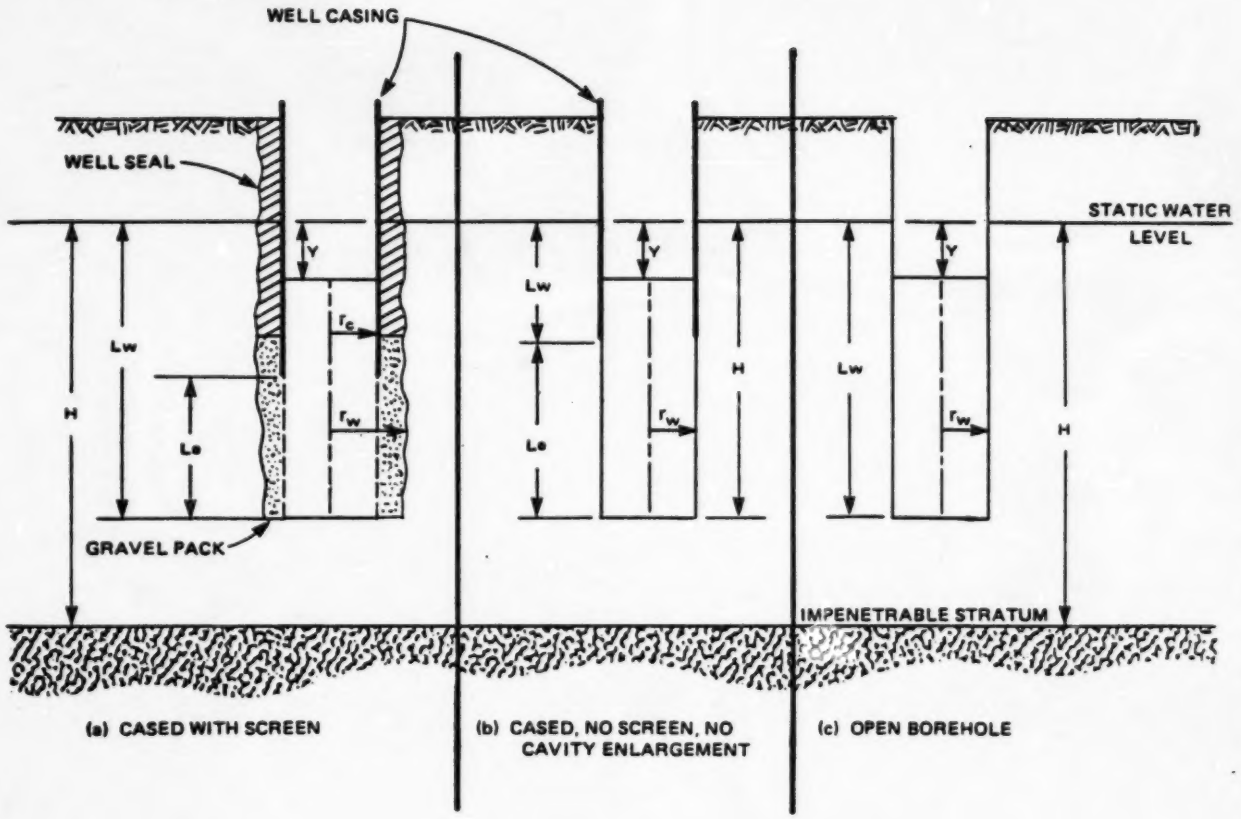

Figure 1.4-3 --Variable definitions for slug tests in unconfined materials. Cased wells are open at the bottom.

as the upper boundary of the zone to be tested was developed by Bouwer and Rice (1976). The geometry and dimensions that are required to be known for the method are shown in Figure 1.4-3. The test is accomplished by effecting a sudden change in fluid potential in the well by withdrawal of either a bailer or submersed float as discussed in Section 1.4.1.2. Water-level changes can be monitored with either a pressure transducer and recorder, a wetted steel tape, or an electric water-level sounder. For highly permeable formations, a rapid-response transducer and recorder system is required. The resolution of the transducer should be about 0.01 m.

1.4.3.3 Calculations. The hydraulic conductivity is calculated using the following equation in the notation of this report, taken from Bouwer and Rice (1976)

$$K = \frac{r_c^2 \ln \bar{R}/r_w}{2 L_e t} \ln \frac{Y_o}{Y} , \qquad (3)$$

where r_c, r_w, L_e, t, Y, and K have been previously defined or are defined in Figure 1.4-2(a). Y_o is the value of Y immediately after withdrawal of the slug of water. The term $\bar{R}$ is an effective radius that is computed using the following equation given by Bouwer and Rice (1976).

$$\ln \frac{\bar{R}}{r_w} = \left\{ \frac{1.1}{\ln (L_w/r_w} + \frac{A + B \ln[(H_o-L_w)/r_w]}{(L_e/r_w)} \right\}^{-1} , \qquad (4)$$

for wells that do not fully penetrate the aquifer. If the quantity $(H_o-L_w)/r_w)$ is larger than 6, a value of 6 should be used.

For wells that completely penetrate the aquifer, the following equation is used:

$$\ln \frac{\bar{R}}{r_w} = \left(\frac{1.1}{\ln (L_w/r_w)} + \frac{C}{L_e/r_w} \right)^{-1}, \qquad (5)$$

(Bouwer, 1976). The values of the constants A, B, and C are given by Figure 1.4-4 (Bouwer and Rice, 1976).

For both cases, straight-line portions of plots of the logarithm of Y or Y_o/Y against time should be used to determine the slope, $\frac{\ln Yo/Y}{t}$.

Additional methods for tests under unconfined conditions are summarized by Bower (1976) on pages 117-122. These methods are modifications of the cased-well method described above that apply either to an uncased borehole or to a well or piezometer in which the diameter of the casing and the borehole are the same (Figures 1.4-3(b) and (c).

1.4.3.4 Sources of Error. The method assumes that flow of water from above is negligible. If this assumption cannot be met, the conductivities may be in error. Sufficient flow from the unsaturated zone by drainage would result in a high conductivity value. Errors caused by measuring water levels and recording time are similar to those discussed in Sections 1.4.1.4 and 1.4.2.4.

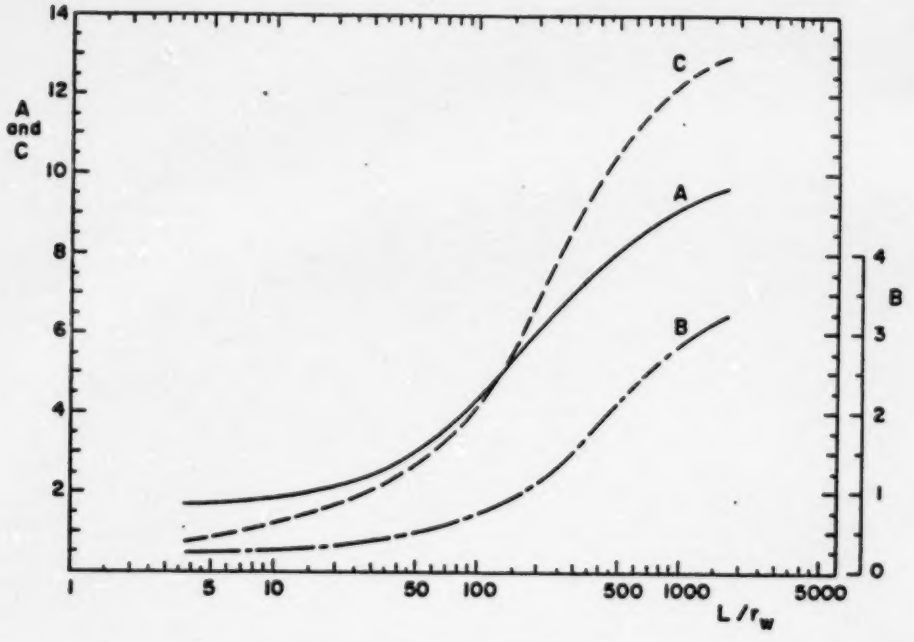

Figure 1.4-4 --Curves defining coefficients A, B, and C in equations 13 and 14 as a function of the ratio L/rw. Source: Bower and Rice, 1976.

1.5 MULTIPLE WELL TESTS

Hydraulic conductivity can also be determined by conventional pumping tests in which water is continuously withdrawn or injected using one well, and the water-level response is measured over time in or near more observation wells. These methods generally test larger portions of aquifers than the single well test discussed in Section 1.4. For some circumstances these tests may be appropriate in obtaining data to use in satisfying requirements of Part 264 Subpart F. However, the large possibility for non-uniqueness in interpretation, problems involved in pumping contaminated fluids, and the expense of conducting such tests generally preclude their use in problems of contaminant hydrogeology. The following references give excellent discussions of the design and interpretation of these tests: Lohman (1972), Stallman (1971), and Walton (1970).

1.6 FRACTURED MEDIA

Determining the hydraulic properties of fractured media is a difficult process. Darcy's Law is not strictly applicable to flow through fractures. However, it can be applied empirically to large bodies of fractured rock if the fractures are spaced closely enough so that the rock acts hydraulically in a manner similar to granular porous media. For rocks with low fracture density, analyzing flow in individual fissures may be necessary. If these fissures are wide, flow may not be laminar and Darcy's

Law does not apply.

The upper limit of Darcy's Law can be determined with the help of the Reynold's number, R_e, defined for porous media as

$$R_e = \frac{\rho v d}{\mu}$$

where ρ = density

μ = viscosity

v = specific discharge

d = a representative length dimension for the porous medium (e.g., mean pore dimension, mean grain diameter, etc.)

It is widely used to distinguish between laminar flow occuring at low velocities and turbulent flow at higher velocities. Darcy's Law generally remains valid for R_e values between 1 and 10. In wide fractures, R_e can exceed this limit, making flow analysis very difficult.

Furthermore, since fractured rock has low porosity, expansion and contraction due to hydraulic and pressure head stress affects the size of the fractures. Thus K becomes a function of this stress, and is no longer constant.

Finally, determining fractured flow is difficult because the orientation of fractures and density of their spacings in different directions can cause anisotropy and trending heterogeneity for K values. With all of these difficulties, a methodology for estimating K in fractured media is beyond the scope of this document. The investigator should consult Sowers (1981) for guidance in analyzing flow through fractured media.

DETERMINATION OF EFFECTIVE POROSITY

SECTION 2.0

Calculation of time of travel (TOT) of ground water to evaluate the vulnerability of the saturated zone requires data on effective porosity, n_e, with respect to flow through the porous media. Effective porosity is usually less than total porosity in that only the interconnected pore space through which fluid flow occurs is of interest. Effective porosity does not take into consideration the pore space in which fluid is practically immobile. Effective porosity is less than total porosity in fine textured medium where adhesion (i.e., the attraction of molecules of fluid to adjacent solid surfaces of the porous matrix) is important or when the porous matrix includes a large portion of dead-end pores. (Bear, 1979)

2.1 Specific Yield in the Unconfined Aquifer

Ground-water and drainage engineers often equate the term effective porosity with the specific yield, Sy, when referring to an unconfined aquifer where the water table is at depth equal to several times the height of the capillary fringe. In these cases, the term drainable porosity is also used.

Specific yield, Sy, is defined as the volume of water that an unconfined aquifer releases from storage per unit decline in the water table. As discussed by Freeze & Cherry (1979), the idea of specific yield is best visualized with reference to the saturated-unsaturated interaction it represents. Figure 2.0-1

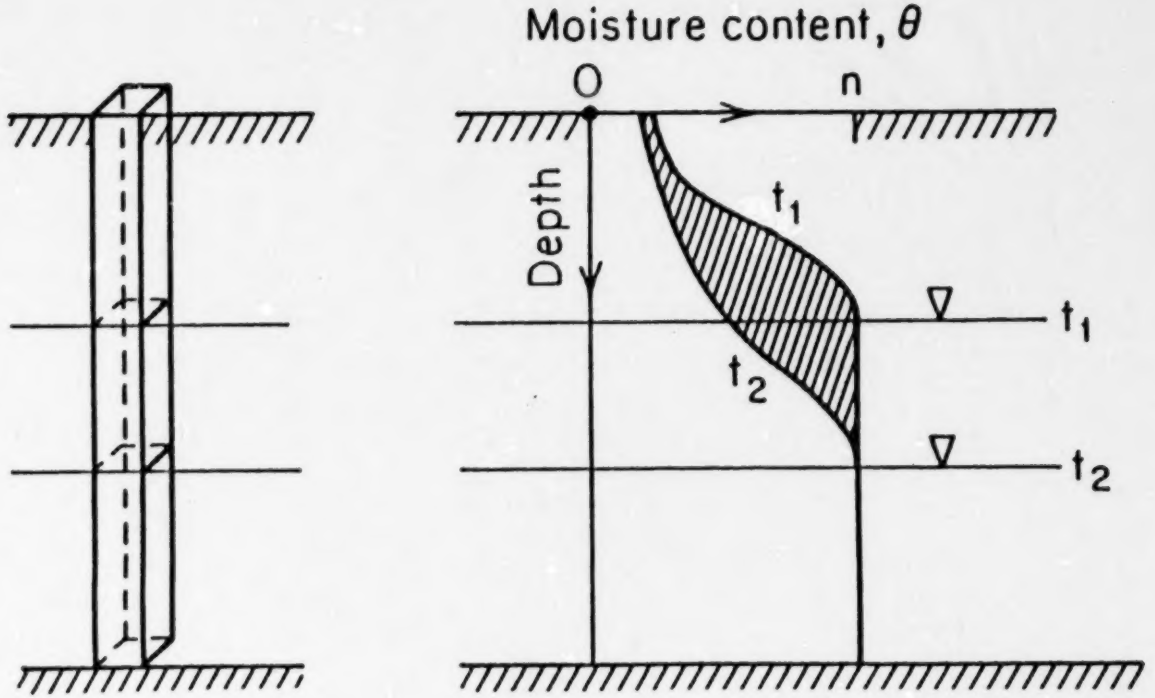

Figure 2.0-1 Concept of specific yield viewed in terms of the unsaturated moisture profiles above the water table. (Freeze & Cherry, 1979)

shows the water-table position and the vertical profile of moisture content vs. depth in the unsaturated zone at two times, t_1 and t_2. The cross hatched area represents the volume of water released from storage in a volume of unit cross section. If the water-table drop represents a unit decline, the cross hatched area represents the specific yield, Sy.

The volume of water retained in an aquifer per unit area and unit decline of the water table is called specific retention, Sr. In a homogeneous isotropic soil with a sufficiently deep water table, Sy + Sr = n when n is the total porosity and specific retention is identical to the field capacity of the soil. Under such conditions, Figure 2.0-2 shows the relationship between specific yield and specific retention for various soils. (Bear, 1979)

Laboratory values of specific yield usually differ from those taken in the field due to the effects of

- aquifer stratification,
- slow drainage of materials above the water table,
- air entrapment in the zone below the water table,
- water table positions,
- the rate of change of the water table elevation.

Actual yields from field tests are reduced up to one-third of laboratory values of Sy. Therefore, McWhorter and Sunada (1977) differentiate between laboratory and field values by defining a bulk parameter, apparent specific yield, Sya, that incorporates these field influences. Because apparent specific yield depends

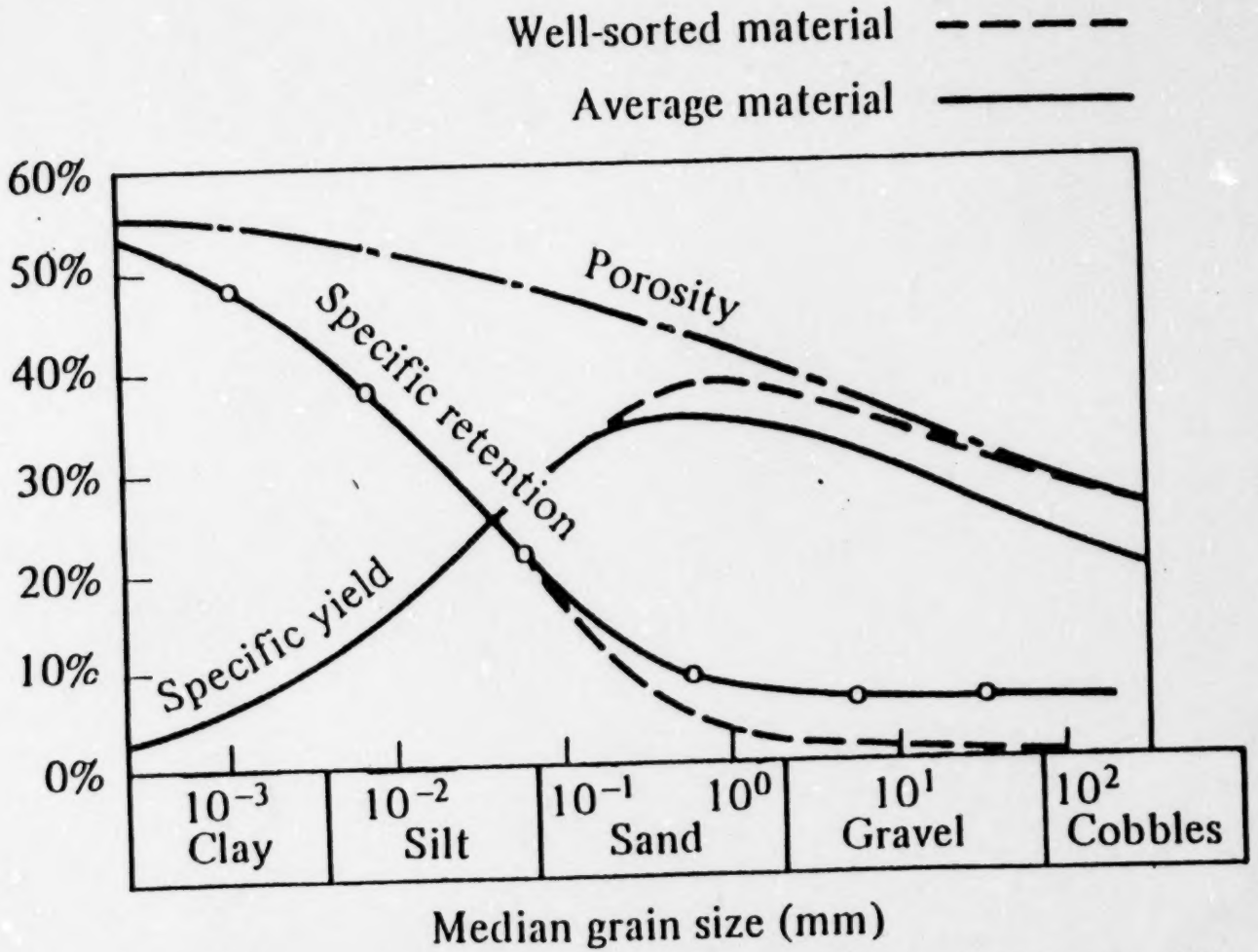

Figure 2.0-2 Relationship between specific yield and grain size (from Conkling et. al., 1936, as modified by Davis and DeWiest, 1966) Bear, 1979

on more than just the physical properties of porous solids, values of apparent specific yield may bear little or no relation to the specific yield. Field determination of apparent specific yield as defined above can be made from analysis of aquifer test data using the Theis solution or the Jacob method (when applicable) as described by McWhorter & Sunada. Field determined values of apparent specific yields are preferred over laboratory values for determining the TOT_{100} since they provide a more accurate representation of the drainage porosity of the water-table aquifer.

2.2 Confined Aquifers

Time of travel calculations as discussed in this document concern ground-water flow along a 100 foot flow line originating at the base of the hazardous waste unit where ground-water movement through saturated zones usually occurs under phreatic (unconfined) conditions. However some flow lines may originate or travel through a confined aquifer. Determination of effective porosity for confined aquifers is rather different than for an unconfined aquifer.

First, the capacity of confined aquifers to release water from storage is markedly different from that of unconfined aquifers. The storage capacity of water-table aquifers, termed specific yield, is representative of the effective porosity of the porous media under homogeneous, isotropic conditions (Section 2.1). As discussed by Freeze & Cherry, water released from storage in a confined aquifer, termed storativity, is not derived from drainage

of the voids as is the case in unconfined aquifers. Rather, it is a function of the porosity of the aquifer material, the secondary effects of water expansion and overburden stress, and aquifer geometry. Therefore, storativity values for confined aquifers should not be used as default values for effective porosity.

Effective porosity for a confined aquifer may be best approximated by laboratory tests run on samples taken from the site, in order to bypass the secondary effects incorporated into storativity values, yet still yield an effective porosity that is as site-specific as possible.

2.3 Tabulated Values of Effective Porosity

Selection of tabulated values of effective porosity based on soil texture classification (Table 3.2-2 in Guidance Criteria for Identifying Areas of Vulnerable Hydrogeology: RCRA Statutory Interpretive Guidance, June 1986) must consider site-specific conditions when evaluating the vulnerability of the ground water to waste constituents. The tabulated values are valid approximations of effective porosity only in homogeneous geologic units composed of relatively coarse materials in which the water table is at a sufficient depth so as to eliminate any influence from the capillary fringe. For example, recent studies indicate that the water in some unweathered glacial tills in connate water remaining from the time of deposition (Barari and Hedges, 1985; Bradbury et al., 1985). This suggests that ground-water flow in some materials may be very slow or nonexistent. The tabulated

values should be reduced up to one-third to incorporate the influence of factors such as air entrapped near the water table, stratification of materials above the water table, water table position and the rate of change of the water table elevation (McWhorter and Sunada, 1977).

For confined aquifers where storativity values are inaccurate, and for tight formations where specific yield values are unobtainable from field tests, tabulated values may be used as guidelines for estimating effective porosity.

FACTORS AFFECTING CHANGES IN HYDRAULIC GRADIENT

SECTION 3.0

Accurate determination of vertical and horizontal hydraulic gradients is very important in characterizing a site's flow regime. Overall characterization of hydraulic gradient (i) should be done by using nested piezometers that are screened in the same geologic unit, as discussed in Section 3.0 of the main text, in Appendix B, and in the RCRA Technical Enforcement Guidance Document U.S.EPA (Draft) 1985, (TEGD). Because methods for determining hydraulic gradient are well-documented, this section will only discuss factors that influence variations in (i) over time.

Seasonal, temporal, and artificially-induced variations in ground-water flow and in corresponding hydraulic gradients should be evaluated with respect to the resultant effect on TOT calculation. The direction and rate of ground-water flow and the hydraulic gradient, can be influenced by one or more of the following external factors:

- well pumping
- tidal processes and fluctuation
- intermittent natural variation in river stage (e.g., bank storage)
- artificial recharge
- natural seasonal variations
- construction activities or change in land use

Off-site or on-site well pumping may effect both the rate and direction of ground-water flow in time-continuous or

discontinuous patterns. Well water-level measurements must be frequent enough to detect such water use patterns.

As discussed in the TEGD, natural processes such as riverine, estuarine, or marine tidal movement may result in variations of well water levels and/or ground-water quality. Ground-water/stream flow interactions often influence the hydraulic gradient of the ground water in the area adjacent to the stream. An increase in river stage may induce flow into stream banks creating a temporary reversal of ground-water flow as shown in Figure 3.0-1. As the river stage declines, the flow is reversed. Transitional patterns that may shift ground-water flow directions must be evaluated with respect to the effect on the vulnerability of the aquifer.

Short-term recharge patterns may affect ground-water flow patterns that are markedly different from ground-water flow patterns from seasonal averages. Selection of the hydraulic gradient term in the time of travel calculation should incorporate any variation in ground-water flow that may result from seasonal fluctuations. Short-term fluctuations in the ground-water flow pattern that result from dewatering due to construction, changes in land use, or artificial recharge should also be evaluated in the determination of the hydraulic gradient (see Figure 3.0-2).

The frequency of well water-level measurements from which hydraulic gradients are determined will depend upon the nature of the particular processes influencing ground-water flow at the site. Well water-level measurements taken on a monthly basis may be adequate to characterize natural seasonal variations.

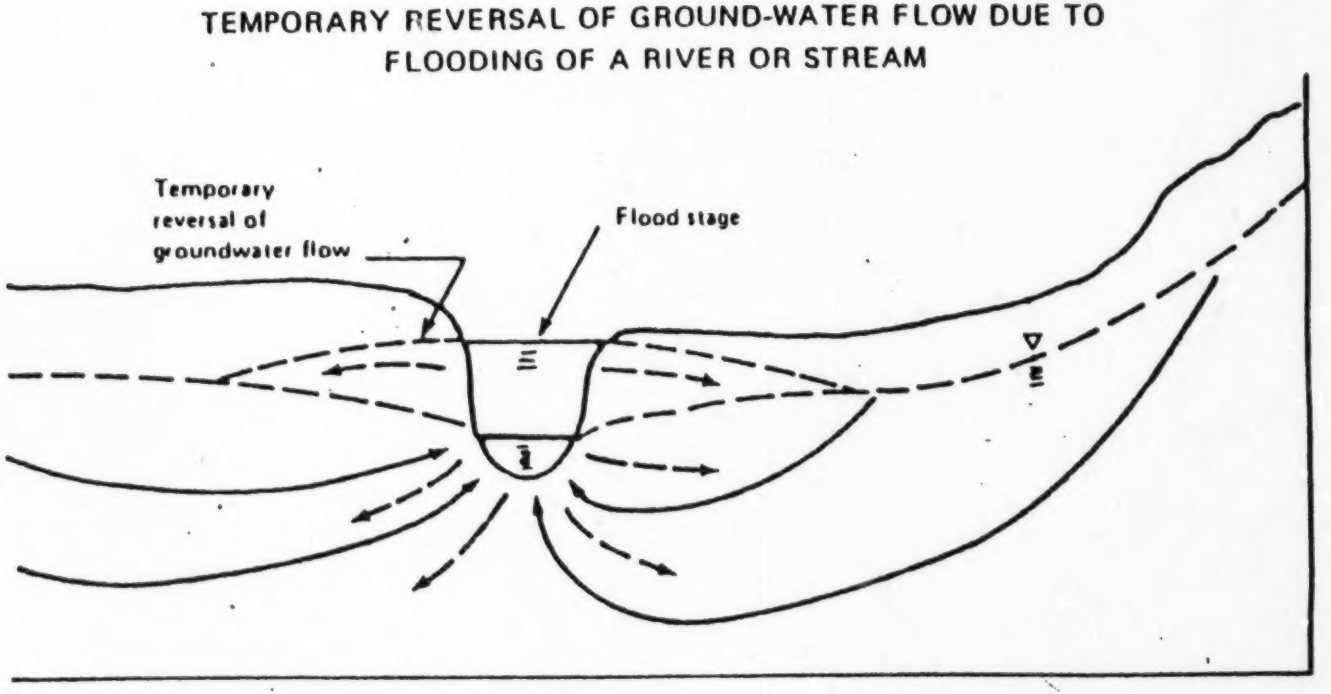

Figure 3.0-1 Diagram of how temporal changes in hydraulic gradient affect the flow paths of groundwater.

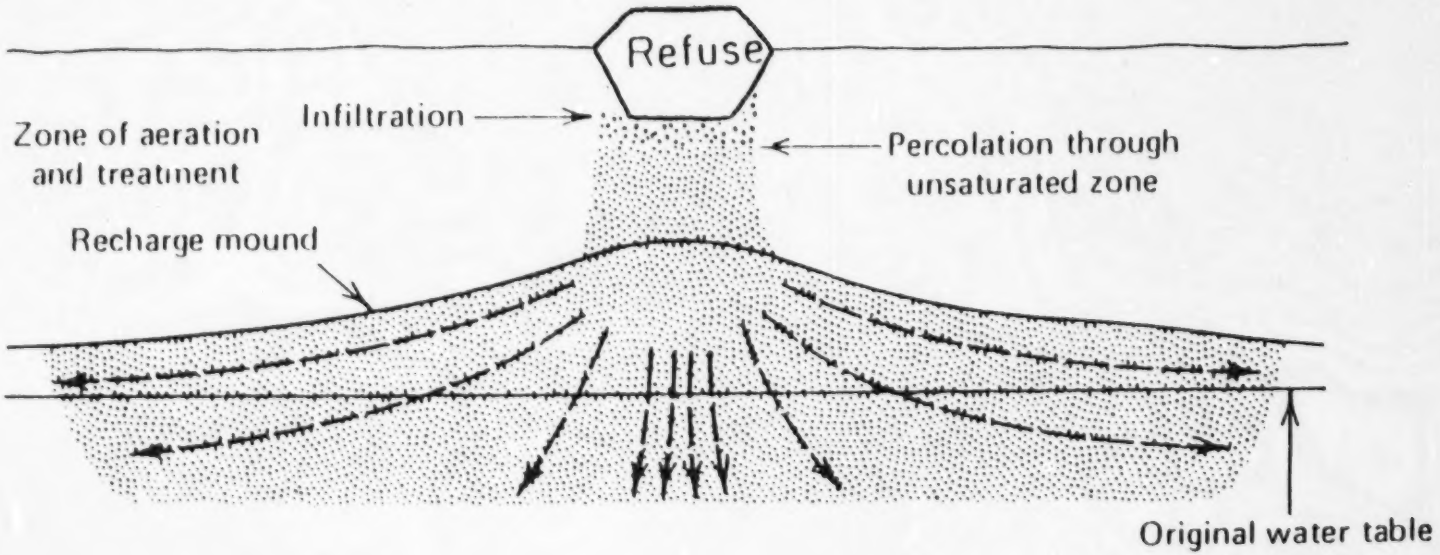

Figure 3.0-2. Illustration of how artificial recharge through an unsaturated zone from a waste unit causes a recharge mound which changes the initial head in the saturated zone.

However, some daily water-level measurements may be required to evaluate the influence of external factors such as well pumping, dewatering due to construction, or artificial recharge. Riverine, estuarine, or marine tidal influences may affect ground-water flow patterns over a shorter time period making hourly or continuous water level monitoring desirable. Continuous water level monitoring should be performed until a pattern of general water level fluctuation is determined for the site. Minimum and maximum fluctuations of water level dependent upon site conditions (i.e., external factors affecting water level and/or natural factors such as tidal influences) should be carefully considered.

Variations in hydraulic gradient determined from ground-water level monitoring will result in a range of ground-water flow velocities and possible variaton of flow direction. Flow nets should be updated to reflect hydraulic gradient fluctuations in order to evaluate a 'worst-case' 100-foot flow line. Time of travel calculations should be made over the range of ground-water velocities to account for the effect of seasonal and temporal factors on the ground-water flow system. For example, Figure 3.0-3 illustrates that during a low water table, the 'worst-case' 100 foot flow line would travel down into the aquifer. However, during a season with high precipitation, another principal flow line would appear, moving horizontally out along a near surface 'basement-seepage' pathway. Further evaluation would be necessary in this case to calculate which flow path would represent the fastest TOT.

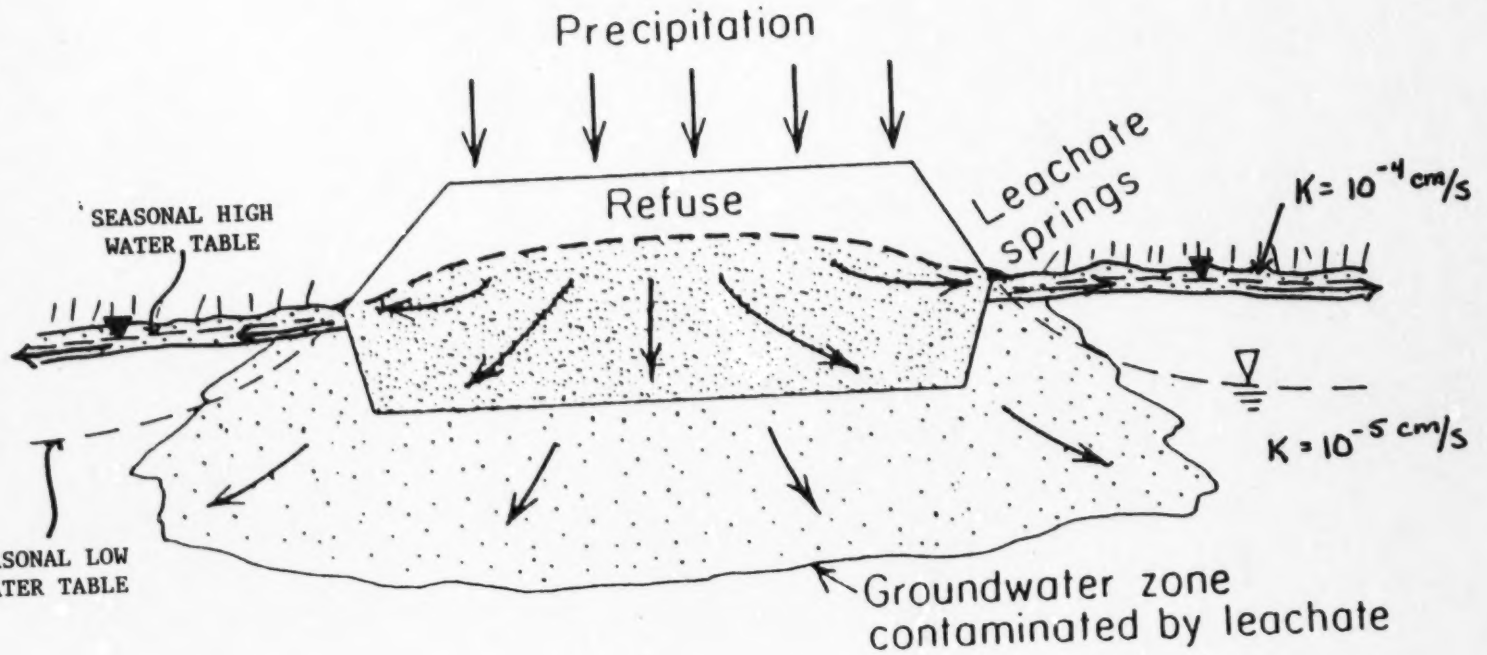

Figure 3.0-3 Diagram of mounding in the saturated zone. Mounding within the waste unit causes an increase in hydraulic gradient, providing a greater driving force for the contaminant plume. Also note that changes in the seasonal precipitation change the water table elevation, opening a new shallow migration path along the more permeable upper soil level.

The initial head as a result of infiltration through a landfill cover and the build up of leachate on the bottom liner must be determined. The Hydrologic Evaluation of Land Performance (HELP) Model can be used to estimate water movement across, into, through, and out of landfills for a wide variety of landfill designs. In the context of evaluating vulnerability as a function of hydraulic gradient, the build up of leachate on or beneath the landfill liner and its related impact on flow velocity is of concern. Section 5 of the U.S. EPA Draft Background Document entitled, Technical Support for Development and Analysis of Hazardous Waste Disposal Regulations, March 1986, addresses the use of the HELP model in estimating head at a landfill liner. The HELP model expresses leachate head on the liner in inches at designated time intervals. The calculation techniques and inherent assumptions associated with the HELP model are discussed in the referenced Draft Background document. The major assumption impacting the accuracy of leachate head is that of fully saturated conditions within the liner. This assumption must be considered in determining hydraulic gradient for calculating flow velocity.

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